CRREL REPORT 91-12

Evaluation of a Portable Electromagnetic Induction Instrument for Measuring Sea Ice Thickness

Austin Kovacs and Rexford M. Morey

June 1991

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

COVER: EM31-PM device on Beaufort Sea.

CRREL Report 91-12

U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Evaluation of a Portable Electromagnetic Induction Instrument for Measuring Sea Ice Thickness

Austin Kovacs and Rexford M. Morey

June 1991

Prepared for
U.S. DEPT. OF NAVY

PREFACE

This report was prepared by Austin Kovacs, Research Civil Engineer, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory, and by Rexford M. Morey, a consultant to CRREL.

The authors wish to acknowledge the field assistance of Deborah Diemand and John Kalafut of CRREL, who assisted in the Alaska field study. The review comments of J. Duncan McNeill, Geonics Limited, and Alex Becker, University of California, Berkley, are also acknowledged.

Funding for this study was provided by the U.S. Department of Navy, Naval Oceanographic and Atmospheric Research Laboratory, under contract N6845286MP6003, and the Naval Civil Engineering Laboratory, under contract N000140WX4B714.

CONTENTS

Preface	ii
Introduction	1
EM31 Sounding concepts	1
Previous EMI studies	2
Beaufort Sea field trials	3
EM31 Conductivity reading versus sea ice thickness	9
General comments	16
Literature cited	17
Abstract	19

ILLUSTRATIONS

Figure

1. EM31-PM instrument-determined versus tape-measured instrument distance to a 2.5-S/m-conductivity seawater	4
2. Ice relief along a 1.3-km-long survey line across first-year sea ice	4
3. Electric drill and gas engine powered units used to drill 5-cm-diameter ice thickness holes	5
4. Typical EM31-PM instrument field use with the instrument set on the surface during a snow plus ice thickness measurement	6
5. EM31-PM instrument-determined versus tape-measured distance to seawater at various stations along a 1.3-km-long track across level and ridged first-year sea ice	6
6. EM31-PM instrument-determined versus tape-measured distance to seawater	8
7. A replot of the data in Figure 6 to show that regression lines passing through each test data set do not intercept zero	8
8. EM31-PM instrument-determined distance to seawater when 3.5 S/m was set into the instrument for the water conductivity versus the EM31-PM instrument-determined distance to seawater when the correct conductivity of 2.5 S/m was used for the water	9
9. Em31-measured conductivity versus tape-measured instrument distance to 2.5-S/m conductivity seawater	10
10. EM-31 measured and computer-code determined conductivity versus tape-measured instrument distance to 2.5-S/m-conductivity seawater	11
11. Ice thickness and EM31 instrument stand-off distance to seawater determined from EM31 measurements versus tape-measured distance to the seawater	12
12. Position of EM31 instrument when set on ladder step	12
13. Theoretical EM31 conductivity reading versus instrument height above 2.5- and 3.0-S/m conductivity seawater	14
14. Theoretical EM31 conductivity reading versus instrument height above 2.5-S/m-conductivity seawater covered with ice of 10- and 50-mS/m bulk conductivity	15
15. Theoretical EM31 conductivity reading versus instrument height above seawater	16

TABLES

Table

1. Ladder test data giving the tape-measured distance from the EM31-PM to the ice surface and ice/water interface and the instrument-determined distance to the seawater for different calibration heights and seawater conductivities 7
2. EM31-PM instrument-determined and computer-code-calculated apparent conductivity versus instrument distance to seawater 10
3. Computer-code-calculated distance to seawater and sea ice thickness using the EM31 field-determined apparent conductivities versus instrument elevation above the seawater 11
4. Theoretical versus measured EM31 conductivity as a function of instrument height above 2.04-m-thick sea ice and instrument tilt angle correction required to produce agreement between the theoretical conductivity for the vertical co-planar coils on the EM31 and the actual instrument field reading 13

Evaluation of a Portable Electromagnetic Induction Instrument for Measuring Sea Ice Thickness

AUSTIN KOVACS AND REXFORD M. MOREY

INTRODUCTION

Sea ice is a multi-component medium. Its constituent parts are fresh ice, liquid brine inclusions, gas pockets and, depending upon eutectic factors, solid salt crystals. The volume of fresh ice is by far the larger fraction, typically in excess of 95%. Sea ice is classified by age (first-year, second-year and multi-year) and by morphology. Variations in growth, melt and deformation processes result in ice formations of complex shape, structure, and brine and gas contents. In particular, the complex structure and liquid inclusion variations have greatly limited our ability to remotely measure sea ice thickness. This is especially true for sounding systems operating at VHF frequencies and above. At these frequencies, the propagation of electromagnetic energy in sea ice suffers high attenuation as a result of the conductive brine inclusions that increase in volume with depth (Kovacs et al. 1987a). Kovacs et al. (1987a) showed that the conductivity of sea ice varies with ice depth, increasing temperature and brine volume. However, the bulk dc conductivity of Arctic sea ice seldom exceeds 0.05 S/m. Only during the early part of the melt season, when the solid salts, which precipitated out during the cold winter months, redissolve to increase the sea ice brine volume, might the bulk conductivity reach about 0.07 S/m.

The capability of remotely measuring homogeneous sea ice thickness, to a high degree of accuracy, using a hand-held instrument has long been desired by those needing to make quick assessments of sea ice bearing capacity for aircraft and vehicle operations on the Arctic Ocean pack ice. Many techniques have been tried, most with limited success because of the sea ice brine content and related ice conductivity. Most of these devices would not qualify as being hand-held and highly portable except for electromagnetic induction (EMI) sounding equipment. Since these EMI systems generally operate in the VLF frequency band, the measurements are significantly less affected by the relatively low bulk conductivity of the sea ice than systems operating in higher frequency bands.

This report discusses the results obtained in April 1990 using a Geonics EM31-D (henceforth called EM31) terrain conductivity measurement instrument with a plug-in processor module that provides a digital display of sea ice thickness. Also discussed is a simple method for using just the EM31's conductivity measurement to determine sea ice thickness.

EM31 SOUNDING CONCEPTS

The Geonics EM31 is a 9-kg, man-portable instrument designed to measure apparent ground conductivity by means of electromagnetic induction (Geonics, Ltd. 1984). It has a transmit (T_x) coil and a receive (R_x) coil that function as magnetic dipole antennas. The coils are spaced 3.66 m apart at each end of a tubular support. For sea ice thickness sounding, the coils were mounted vertically co-planar and therefore functioned as horizontal dipole antennas. Sea ice is relatively resistive and thus quite transparent at the EM31's operating frequency. Therefore, during sea ice sounding the transmitted (primary) electromagnetic field induces eddy currents primarily in the conductive seawater. These currents in turn produce a secondary electromagnetic field that is sensed, along with the primary electromagnetic field, by the receiver coil. The EM31 is designed to measure the magnitude of the in-phase and quadrature components of the secondary magnetic field. These components are normalized by dividing them by the magnitude of the received primary electromagnetic field component. Given that sea ice is relatively transparent at 9.8 kHz, the response measured by the EM31 will be a strong function of the instrument height above and the conductivity of the seawater. Therefore, accurate measurement of the electromagnetic field response from the seawater and a full solution analysis of the data using the numerical procedure of Anderson (1979) should provide a good estimate of instrument–seawater distance, or the ice thickness, when the EM31 is resting on ice of uniform thickness.

The measured EM31 response is not a point measurement but an integrated depth–volume measurement with a quasi-circular footprint. The footprint diameter is on the order of two or three times the instrument's height above the conductive seawater surface, depending on T_X–T_R coil orientation (Kovacs et al. 1987b, Liu and Becker 1990). Therefore, as the instrument is elevated above the seawater, the footprint, about three times the EM31 height above seawater for the vertical co-planar coil orientation, increases. For ice of relatively uniform thickness, this should not pose a problem, but on ice with appreciable undulating bottom relief, for example, the bottom of most multi-year sea ice, the resulting instrument-determined ice thickness will be an "average" one for an area around the instrument. That is, the ice thickness measured through a drill hole directly below the instrument on multi-year ice will not likely agree with the ice thickness estimated from the EM31 measured response.

PREVIOUS EMI STUDIES

An early trial using two types of portable EMI instruments was conducted by Sinha (1976). While he did experience equipment calibration problems, he was able to demonstrate the potential of small, lightweight EMI equipment for measuring sea ice thickness. This study was followed by those of Hoekstra et al. (1979) and Hoekstra (1980). The former employed a Geonics EM31 instrument with an operating frequency of 39.2 kHz and the latter study used an EM31 instrument with a now standard operating frequency of 9.8 kHz.

Hoekstra et al. (1979) tested the instrument above saline ice grown in an outside test basin and then on sea ice in Mackenzie Bay, Canada. The test basin measurements were very encouraging in that good correlation was found between the measured in-phase response and the instrument elevation above the ice. This led to the arctic field trial, which was not particularly rewarding. For example, on 2-m-thick sea ice, the ice thickness determined from the instrument measurements varied up to 40%. Another field study was made on the sea ice in Stefansson Sound, located north of Deadhorse, Alaska (Hoekstra 1980). Only seven measurements were made, four on ice 1.70 m thick. The inferred ice thickness at the 1.70-m-thick ice sites varied from about 1.83 to 2.20 m. While these limited results were not especially good, they did indicate that if the instrument was properly calibrated and the measured response properly evaluated, homogeneous first-year sea ice thickness should be reasonably determinable.

Further tests using the EM31 to estimate sea ice thickness were made by the oil industry. The results have not been released. However, as a result of his knowledge of these tests, D.C. Echert at Flow Research, Inc., pursued further evaluation of the EM31 for the remote measurement of sea ice thickness. This included both desk studies and field trials off the Alaskan Beaufort Sea coast near Prudhoe Bay (Echert 1986). The results showed the advantage of using a vertical co-planar (versus horizontal co-planar) coil configuration and demonstrated that with this coil arrangement first-year sea ice thickness could be estimated, generally with a deviation of less than 15% from the drill-hole-measured thickness. This coil orientation was used in all subsequent EM31 sea ice thickness measurement studies. Like Hoekstra (1980), Echert used both the in-phase and quadrature phase components of the received magnetic field for estimating thickness. These results were obtained with the in-phase of an EM31 instrument zero calibrated over highly resistive permafrost. The zero level of the quadrature phase is set by Geonics and does not need recalibration.* Echert indicated that if the instrument had been calibrated over a known thickness of sea ice, significantly better ice thickness estimates may have resulted.

Because of these favorable results, further evaluation of EMI sounding ensued (Echert et al. 1989). The main objective was to provide additional internal data processing capability to a standard 9.8-kHz EM31 instrument that would enable direct numerical display of ice thickness. This was achieved through the use of a look-up table, using the full solution multilayer analysis of Anderson (1979), as provided in Geonics program PCLOOP, and an interpolation algorithm. This approach assumes that the in-phase and quadrature components of the received magnetic field are unique to specific sea ice thickness and sea ice and seawater conductivities. The Flow Research look-up table was developed using 10 mS/m for the bulk conductivity of the sea ice, a seawater conductivity range from 2 to 3 S/m in 0.25-S/m increments, and a sea ice thickness range from 0.25 to 6.0 m in 0.25-m increments. The ice thickness displayed is an interpolation between the tabulated data and the measured EM31 response.

Field testing of the reconfigured EM31 was done in the spring of 1989 on sea ice north of Prudhoe Bay, Alaska (Echert et al. 1989). Sea ice between 0.4 and about 3.2 m thick was measured. For ice over 1 m thick,

*Personal communication with J.D. McNeill, Geonics, Ltd., 1990.

the EM31 and processor module (PM) system estimated ice thickness within about 5% of the drill-hole-measured thickness. However, the instrument-determined values became progressively less accurate, less than the direct tape-measured values, with decreasing ice thickness below 1 m. Echert et al. (1989) suggested that this may have resulted from using a constant bulk sea ice conductivity in the construction of the look-up table that did not adequately address the higher bulk conductivity that can be expected for thinner sea ice (Kovacs et al. 1987a). However, other factors may have affected the results, such as improper instrument calibration, inappropriate look-up tables, etc.

The generally favorable ice measurements obtained with the modified EM31-PM instrument by Echert et al. (1989) indicated that this device may prove useful for gathering ice thickness information during our continued evaluation of airborne electromagnetic induction sounding technology for the measurement of sea ice thickness (Kovacs et al. 1987b, 1989). Therefore, the modified EM31-PM instrument was obtained, from G. White of Flow Research in Kent, Washington, on a trip to Alaska in April 1990 for our study.

On the day the EM31-PM was picked up, White gave us a quick review on how to calibrate and operate the instrument. In addition a brief operations text was provided for future field use. At the time we were not in possession of Hoekstra's or Sinha's papers (previously cited), describing their use of EMI sounding for measuring sea ice thickness, nor did we have the cited reports of Echert with us. We went into the field to use the EM31-PM as a fully developed operational instrument for sea ice thickness measurement and to determine if it could provide thicknesses that were within 5% of the direct drill-hole-measured values as needed for our study.

BEAUFORT SEA FIELD TRIALS

The EM31-PM instrument was first used on first-year sea ice 1.6 to 1.7 m thick. Here, the instrument was calibrated at a site of known snow plus sea ice thickness as determined by a drill hole measurement. It should be pointed out that at all our measurement sites the snow cover was not removed. Therefore, the measured thickness discussed hereafter is that of the combined snow plus sea ice. In the instrument calibration process, the known seawater conductivity was used, which was 2.5 S/m for our study area.

On-ice calibration of the EM31-PM instrument is the most accurate and was the method used. This procedure required that the instrument be elevated at two different heights above the seawater. At each elevation, the distance to the seawater, as determined with a drill hole and tape measurement, was manually entered, via thumbwheel dials, into the PM. The seawater conductivity, 2.5 S/m, was also entered into the PM's memory via the thumbwheel dials. The instrument would then be operated and the measured response used internally to match up with the Flow Research look-up table response values and the given instrument-to-seawater distance. Through this process, the PM's look-up table was calibrated against the measured conditions.

After the instrument was calibrated, it was taken to various locations on the first-year sea ice floe where a measurement was made with the instrument resting on the surface. In addition, at one site the instrument was elevated to heights up to 1 m above the surface and soundings made. At all measurement sites on this ice floe, the instrument provided distances to the ice/water interface that were within 0.10 m of the measured distance.

The instrument was next taken to a nearby area with 0.17 m of sea ice. With the instrument resting on the surface, a reading of ice thickness was made. This reading indicated 0.77 m of sea ice or 0.6 m more than existed.

To determine what the instrument's lower ice thickness limitation might be, it was elevated in increments above the surface by resting it on cardboard boxes. A plot of the EM31-PM instrument-determined distance to the seawater versus the tape-measured distance is shown in Figure 1. This figure suggests that ice thickness, or distance to seawater, of less than about 0.7 m cannot be measured to within ±10% of the true distance when the EM31-PM instrument is resting on the ice surface. However, thin ice should be adequately measurable if the instrument is elevated 0.7 m or more above the ice surface and this distance is then subtracted from the instrument-determined distance to the seawater. Of course, this requires the operator to judge when he may be on ice less than 0.7 m thick and must elevate the instrument. For relatively accurate EMI ice thickness sounding, the EM31 should not be held at waist height while making routine soundings, as variations in the instrument's coil from a vertical co-planar orientation will cause measured response variations that cannot be properly analyzed by the PM.

The results in Figure 1 also show some scatter between the tape-measured distance to seawater and the instrument-determined distance. To further assess this variation, we made measurements with the instrument along a 1.3-km-long line established (not for this study) across first-year sea ice of varying thickness and morphology (Fig. 2). Drill hole stations, for measuring ice thickness along this line, were spaced 5 m apart. EM31-PM instrument soundings were made at 206 of the

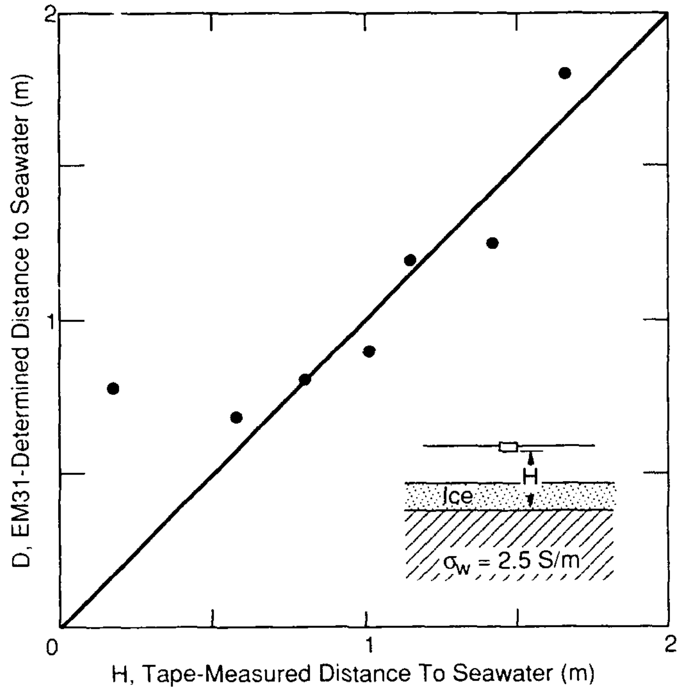


Figure 1. EM31-PM instrument-determined versus tape-measured instrument distance to 2.5-S/m-conductivity seawater. Vertical co-planar coil orientation used.

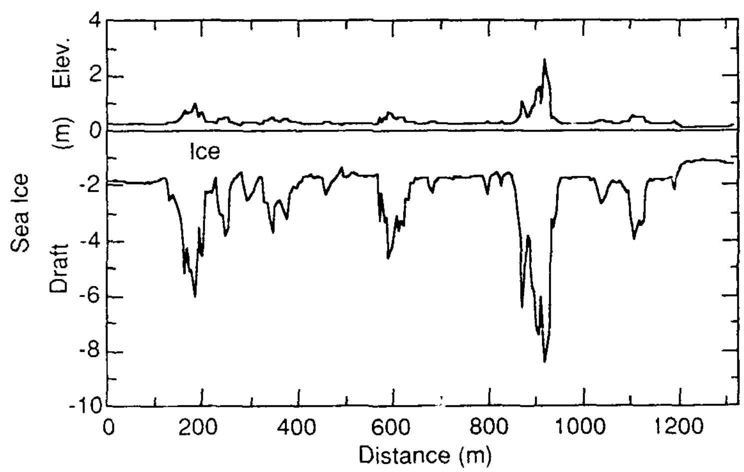


Figure 2. Ice relief along a 1.3-km-long survey line across first-year sea ice. EM31-PM instrument ice thickness soundings were made along this line

stations along the line before drilling (Fig. 3), and taped snow plus ice thickness measurements were made. All EM31-PM sounding measurements were made with the instrument resting on the snow surface as shown in Figure 4.

A plot of the EM31-PM instrument-determined distances to seawater versus the drill-hole-measured distances is shown in Figure 5. The data fall into two regions, one up to about 3.5 m, in which the instrument-determined thicknesses track the measured distance to seawater reasonably well, and a second, in which extremely poor correlation exists for distances to seawater of over 3.5 m. The regression curves through the data representing these two regimes are based on a somewhat arbitrary 3.5-m break point.

The winter of 1989–90 produced unusually thick sea ice. Undeformed first-year sea ice with 0.05 m or less of snow cover was typically 2.1 ± 0.1 m thick. In the lee of pressure ridges, snow drift depths in excess of 1 m were occasionally encountered on the level sea ice. Therefore, the stand-off distance between the seawater and the EM31-PM on undeformed sea ice with a snow cover could reach 3 to 3.5 m. The regression line through the 0- to 3.5-m-thick-ice data set does not pass through zero. One may assume that this is caused by the somewhat arbitrary 3.5-m upper bound selected for the data set, as well as the paucity of data at the higher and lower distances or ice thickness. The data in Figure 5 suggest that EM31-PM sounding can provide a good estimate of snow and ice thickness from about 0.7 to 3 m, but not with an accuracy of ±5% of the directly measured value.

Drill-hole-measured snow plus ice thicknesses over 3.5 m were obtained in areas of deformed ice. The poor agreement between the EM31-PM instrument-determined distance to the seawater and the drill-hole-measured distance in these areas is likely attributable to the highly variable ice/water interface relief in the area of deformed ice and pressure ridges, and to the seawater-filled voids in the ice rubble. These voids and diffused interfaces create conductive inhomogeneities that give rise to an EMI response that is currently not interpretable. Similar unreliable results were noted by Hoekstra (1979), using an EM31 instrument, and by Kovacs et al. (1987b) and Kovacs and Holladay (1989), evaluating an airborne electromagnetic induction device for sounding sea ice thickness.

After reviewing the above results in the field, and given the fact that there was no thick multi-year sea ice in our study area on which to evaluate the EM31-PM instrument, we decided to replicate thicker ice by simply elevating the instrument above uniform 2.04-m-thick sea ice. A wooden stepladder was used to elevate the instrument in increments up to about 2.8 m above the ice surface or 4.8 m above the seawater.

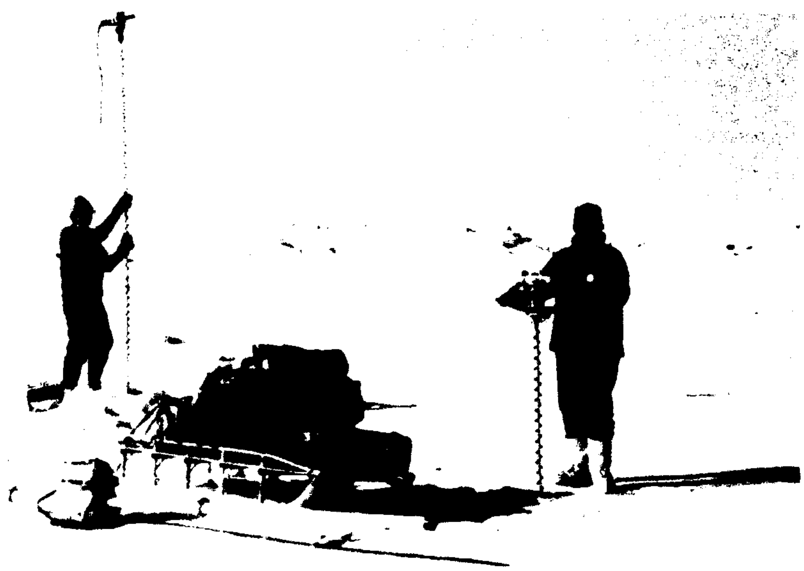


Figure 3. Electric drill and gas engine powered units used to drill 5-cm-diameter ice thickness holes. The EM31-PM electromagnetic induction sounding instrument is resting on the surface in the foreground.

Figure 4. Typical EM31-PM instrument field use with the instrument set on the surface during a snow plus ice thickness measurement.

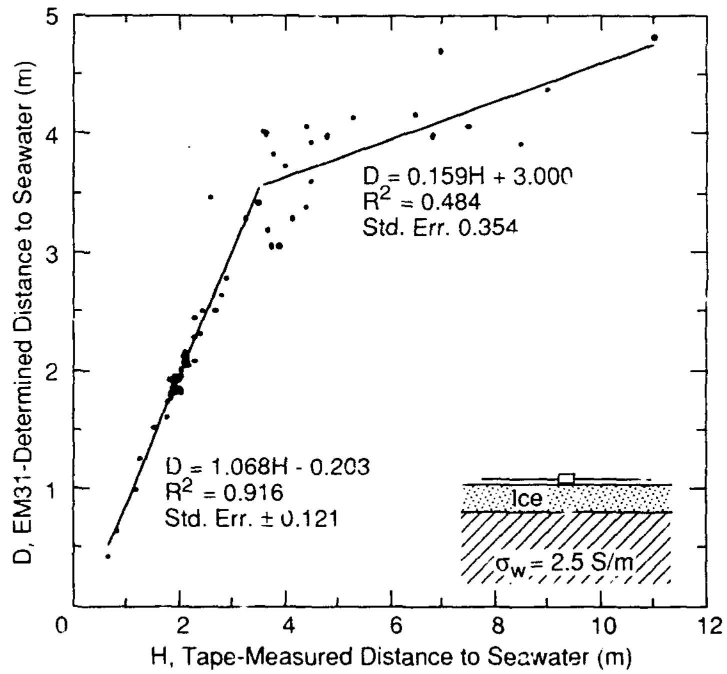


Figure 5. EM31-PM instrument-determined versus tape-measured distance to seawater at various stations along a 1.3-km-long track across level and ridged first-year sea ice

On-ice calibration of the EM31-PM system requires the instrument to be positioned at two different elevations (H_1 and H_2) above the seawater. These elevations, along with the conductivity of the seawater, were manually entered, via thumbwheel dials, into the PM. The calibration procedure was done at several instrument elevations to determine if the height at which the instrument was calibrated affected the EM31-PM instrument-determined ice thickness or the distance to the seawater. In addition, for one calibration a value of 3.5 S/m was input for the conductivity of the seawater under the ice versus the true value of 2.5 S/m as determined by use of an in-situ conductivity probe.

The instrument calibrations were made at H_1 and H_2 distances of 2.04 and 2.89 m, 2.04 and 3.45 m, and 3.16 and 4.02 m using the correct seawater conductivity of 2.5 S/m. For the case where 3.5 S/m was used for the seawater conductivity, the H_1 and H_2 calibration heights were 2.04 and 3.45 m respectively.

After the instrument was calibrated, the unit was set on the ice surface and a distance-to-seawater measurement made. This was followed by setting the instrument on successive steps of the ladder and repeating the distance measurement. The resulting data are listed in Table 1 and graphically shown in Figure 6.

The plots in Figure 6 indicate that different H_1 and H_2 instrument calibration heights have a variable effect on the instrument-determined distance to the seawater. While the spread in the EM31-PM distance determinations for the various H_1 and H_2 calibration heights is on the order of ±5%, in most all cases the resulting distances are greater than the tape-measured distance to the seawater, particularly at distances over 3.5 m. For example, when the true seawater conductivity was used and the instrument was elevated 4.59 m above the seawater, the instrument gave distances of 5.38, 4.88 and 5.13 m for test runs A, B and C respectively (Table 1). The average of these reading is 5.13 m or 0.54 m greater than the tape-measured distance of 4.59 m, a 13% difference. The spread not only becomes larger with increasing distance from the seawater but none of the regression lines passing through the data sets intercept zero as shown in Figure 7. It would appear that the look-up table and interpretation algorithm are not properly analyzing the received electromagnetic response from the seawater.

It is interesting to compare the test B and D data in Table 1. Both data sets were collected with the instrument calibrated at the same H_1 and H_2 elevations, but different values were used during the calibration procedure for the seawater conductivity: 2.5 S/m for test B versus 3.5 S/m for test D. A plot of the data in Figure 8 shows a virtual one-to-one agreement between the test results. This implies that for the test stand-off distances

Table 1. Ladder test data giving the tape-measured distance from the EM31-PM to the ice surface and ice/water interface and the instrument-determined distance to the seawater for different calibration heights and seawater conductivities.

Tape-measured distance to ice surface (m)	*Tape-measured distance to seawater (m)*	*EM31-PM-measured distance to seawater*			
		Test A (m)*	*Test B† (m)*	*Test C** (m)*	*Test D†† (m)*
0.00	2.04	2.03	2.00	2.08	2.00
0.27	2.31	2.22	2.33	2.41	2.25
0.55	2.59	2.53	2.56	2.56	2.51
0.85	2.89	2.86	2.88	2.93	2.82
1.12	3.16	3.18	3.12	3.17	3.09
1.41	3.45	3.63	3.50	3.47	3.46
1.69	3.73	4.00	3.86	3.77	3.76
1.98	4.02	4.33	4.27	4.18	4.24
2.26	4.30	4.92	4.66	4.54	4.61
2.55	4.59	5.38	4.88	5.13	4.87

* Test calibration parameters – H_1 = 2.04 m, H_2 = 2.89 m, Γ_w = 2.5 S/m.

† Test calibration parameters – H_1 = 2.04 m, H_2 = 3.45 m, Γ_w = 2.5 S/m.

** Test calibration parameters – H_1 = 3.16 m, H_2 = 4.02 m, Γ_w = 2.5 S/m.

†† Test calibration parameters – H_1 = 2.04 m, H_2 = 3.45 m, Γ_w = 3.5 S/m.

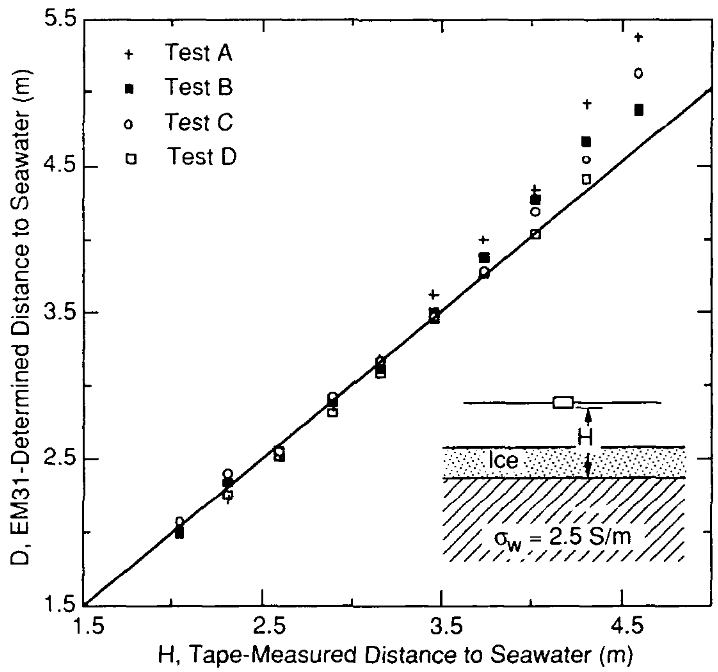


Figure 6. EM31-PM instrument-determined versus tape-measured distance to seawater. Data were obtained by elevating the instrument in increments on a stepladder. Each test represents a different instrument calibration height.

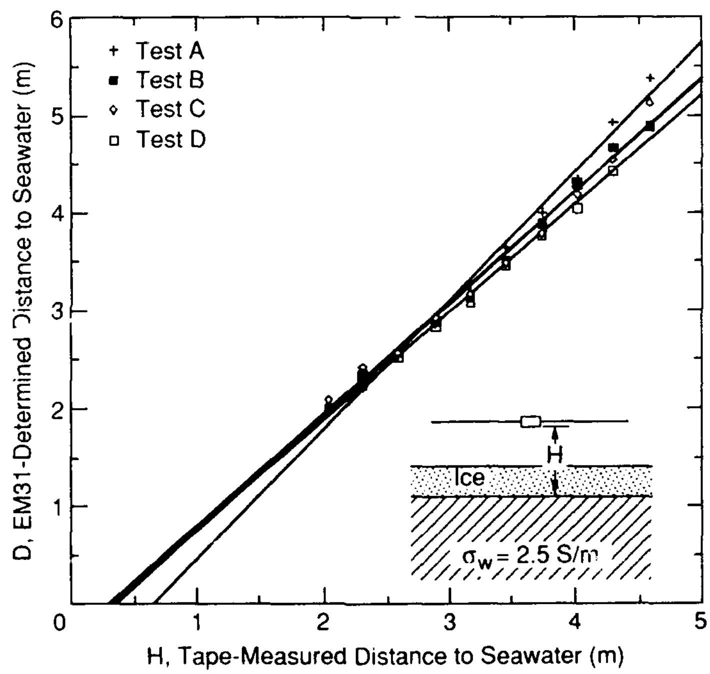


Figure 7. A replot of the data in Figure 6 to show that regression lines passing through each test data set do not intercept zero.

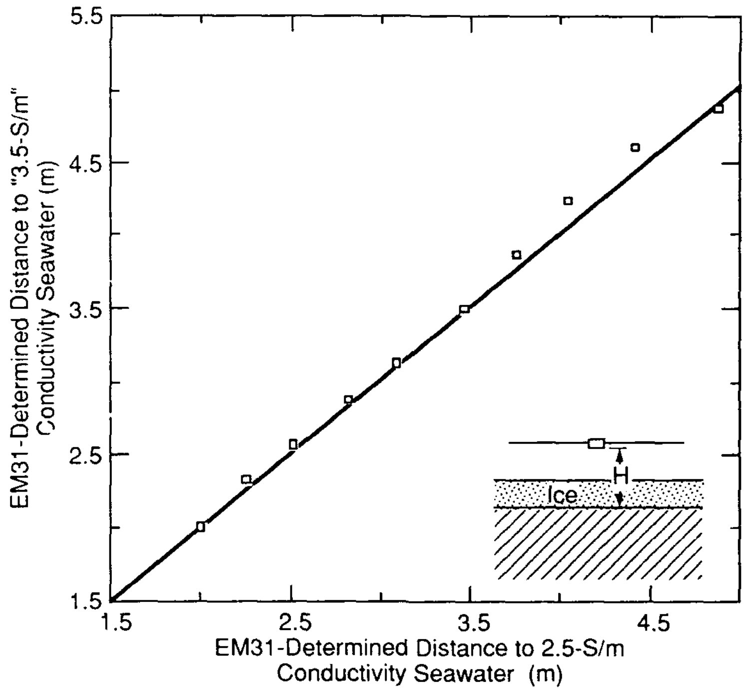


Figure 8. EM31-PM instrument-determined distance to seawater when 3.5 S/m was set into the instrument for the water conductivity versus the EM31-PM instrument-determined distance to seawater when the correct conductivity of 2.5 S/m was used for the water.

the instrument-determined distance to seawater was not affected by using the above seawater conductivities in the calibration procedure. This finding will not hold if the instrument is brought progressively closer to the seawater. When this occurs the response from the seawater becomes exponentially larger and more dependent upon the water's conductivity. It is assumed that the processor module's ice thickness interpretation algorithm takes this effect into account.

EM31 CONDUCTIVITY READING VERSUS SEA ICE THICKNESS

As previously stated the electromagnetic response measured by an EM31 instrument is strongly related to the conductivity of the seawater and the stand-off distance. The conductivity of homogeneous sea ice is about two orders of magnitude less than that of Arctic Ocean seawater, and should have a minimal effect on the electromagnetic field response measured by the instrument. Therefore, we decided to repeat the ladder measurements but only record the EM31's conductivity reading versus instrument distance above the seawater. The results are graphically shown in Figure 9. The data clearly show that a standard off-the-shelf EM31 can provide conductivity measurements, in millisiemens per meter, that are directly related to the instrument height above seawater or to ice thickness.

To further assess this, the Geonics PCLOOP multilayer computer code was used. This program allowed calculation of the response that an EM31 instrument should measure versus height above seawater or when the instrument is resting on sea ice. The program uses operator input values for the seawater and sea ice conductivity, as well as the distance of the EM31 above the seawater, to calculate the apparent conductivity that the instrument should measure under these conditions.

In this analysis the seawater conductivity was set at 2.5 S/m and a 2.04-m-thick sea ice cover with a bulk conductivity of 10 mS/m was used. A comparison of the instrument-determined field reading versus the theoretical apparent conductivity values can be seen in Table 2 and in the plot of these values versus the

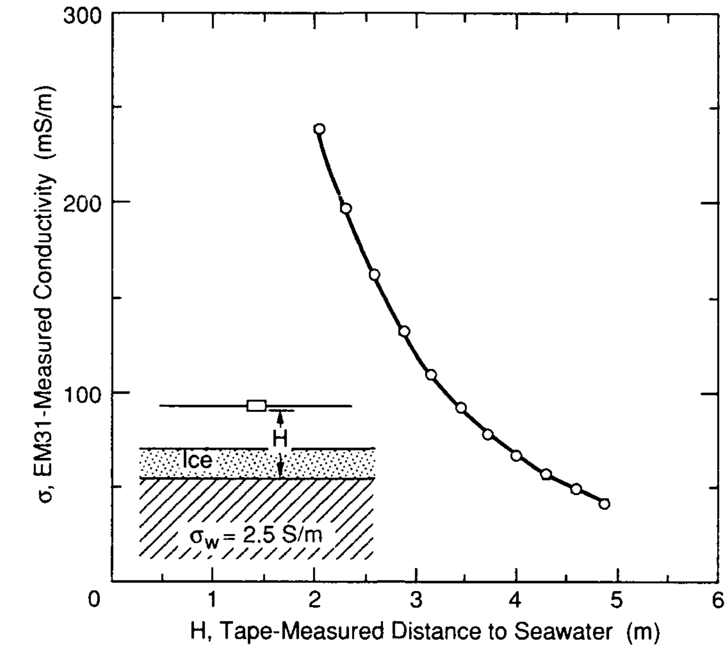


Figure 9. EM31-measured conductivity versus tape-measured instrument distance to 2.5-S/m conductivity seawater.

distance to seawater in Figure 10. Clearly, there is an offset between the EM31-determined and the computer-code-calculated apparent conductivities.

To unravel this discrepancy, we ran the computer code using the EM31-determined conductivities in Table 2 along with the drill-hole-measured ice thickness (2.04 m) and again setting the ice and water conductivities at 10 mS/m and 2.5 S/m, respectively, to determine what the theoretical instrument–seawater stand-off distance would be. The results are listed in Table 3. The indica-

Table 2. EM31-PM instrument-determined and computer-code-calculated apparent conductivity versus instrument distance to seawater.

Tape-measured EM31 distance to sea ice (m)	*Tape-measured EM31 distance to seawater (m)*	*EM31 measured conductivity (mS/m)*	*Code determined conductivity (mS/m)*	*Diff. between EM31 and code conductivities (mS/m)*
0.00	2.04	240	239	1
0.27	2.31	211	197	14
0.55	2.59	172	162	10
0.85	2.89	150	133	17
1.14	3.16	126	110	16
1.14	3.45	112	93	19
1.69	3.73	98	79	19
1.98	4.02	85	67	18
2.26	4.30	72	57	15
2.55	4.59	64	50	14
2.83	4.87	54	42	12

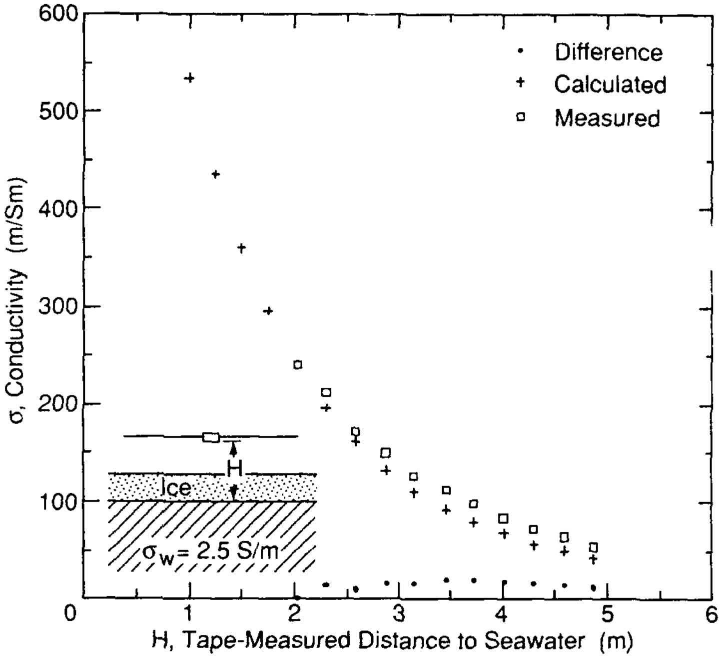


Figure 10. EM31-measured and computer-code determined conductivity versus tape-measured instrument distance to 2.5-S/m-conductivity seawater. Also shown is the difference between the measured and calculated conductivity values versus distance.

tion here is that either the EM31 conductivity determinations are wrong or the computer-program calculated instrument distances to the seawater are in error. From this analysis we found that the computer code consistently calculated lower instrument–seawater stand-off distances than determined by tape measurement. In addition, subtracting column 1 from column 4 in Table 3 gives the results in column 5, which indicate a decreasing ice thickness versus increasing instrument height above the seawater. A plot of these findings is shown in

Table 3. Computer-code-calculated distance to seawater and sea ice thickness using the EM31 field-determined apparent conductivities versus instrument elevation above the seawater.

Tape-measured EM31 distance to sea ice (m)	*Tape-measured EM31 distance to seawater (m)*	*EM31 measured conductivity (mS/m)*	*Calculated distance to seawater (m)*	*Calculated ice thickness (m)*
0	2.04	240	~2.04	~2.04
0.27	2.31	211	2.21	1.94
0.55	2.59	172	2.50	1.95
0.85	2.89	150	2.70	1.85
1.14	3.16	126	2.96	1.82
1.41	3.45	112	3.15	1.74
1.69	3.73	98	3.35	1.66
1.89	4.02	85	3.59	1.61
2.26	4.30	72	3.92	1.66
2.55	4.59	64	4.08	1.53
2.83	4.87	54	4.39	1.56

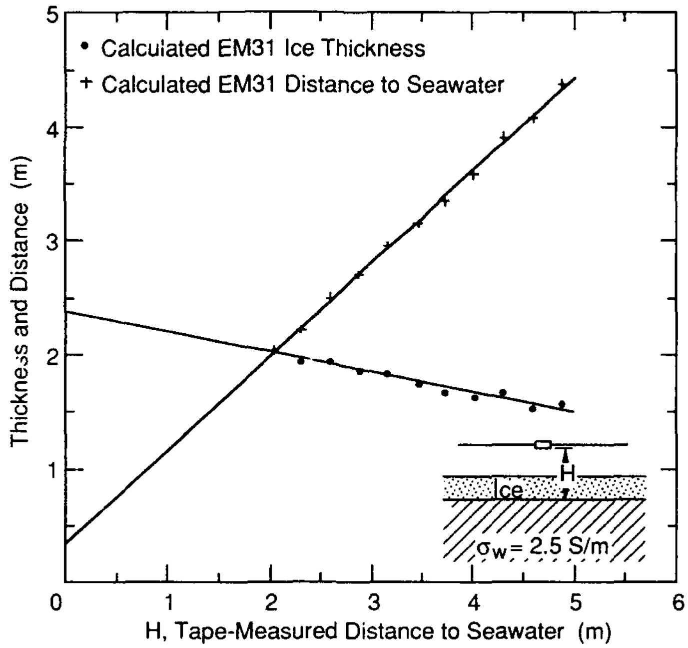


Figure 11. Ice thickness and EM31 instrument stand-off distance to seawater determined from EM31 measurements versus tape-measured distance to the seawater.

Figure 11. Clearly, there is a problem. The problem turns out to be a relatively simple one, but an extremely important one that must be appreciated by anyone choosing to use an EM31 type instrument for sea ice thickness determinations.

Resting the instrument on the ladder steps caused two things to happen. First, the coil support booms, extending out each side of the electronic module, butted up against the ladder sides. This prevented the electronic module from resting flat on the steps (see Fig. 12). Second, above about the fourth step, the tilt was exacerbated by the narrowing of the sides of the ladder and

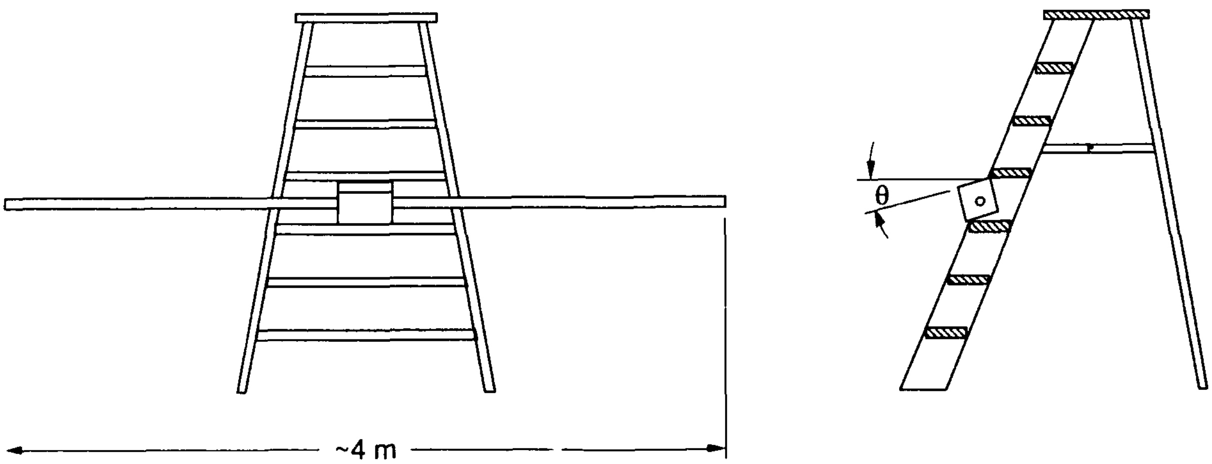


Figure 12. Position of EM31 instrument when set on ladder step.

by the operator, who stated he had a tendency to tilt the unit on the higher steps to make viewing the readout easier. In short, he did not wish to climb any higher on the relatively unstable ladder than was apparently necessary. This was probably a good idea, considering the poor condition of the stepladder used.

Tilting of the EM31 caused the orientation of the vertical co-planar coils to change. Instead of being vertical, as desired and assumed in the computer analysis, the coils were *tilted slightly away from vertical*.

Fortunately, the computer code allows determination of the theoretical conductivity for both a vertical and horizontal co-planar coil position for a given set of input parameters, such as instrument height, seawater conductivity (2.5 S/m), ice thickness (2.04 m), ice conductivity (10 mS/m), etc. Therefore, the computer code was used to recalculate the theoretical conductivity for the vertical and horizontal co-planar coil positions above seawater at which our EM31 field measurements were made. These calculations are given in Table 4 (columns 2 and 3) along with the EM31 reading obtained in the field (column 4). Next, tilt angle corrections were applied to the calculated values in columns 2 and 3 until an angle was found that produced a theoretical conductivity that was in close agreement with the field measurement. For each instrument height, this new value was determined by multiplying the number in column 3 by the cosine of some coil tilt angle θ and adding this value to the value obtained by multiplying the number in column 2 by the sine of the same angle.

The results of this process are given in columns 5 and 6 in Table 4. As expected, when the instrument was resting on the ice surface and was reasonably level, it gave a conductivity reading (column 4) in excellent agreement with the theoretical value shown in column 3. However, when the instrument was placed on the ladder step it was tilted slightly to fit securely in place (Fig. 12). As the instrument was moved onto higher ladder steps the tilt angle became progressively greater, as shown by column 5 in Table 4.

Replotting the above corrected data in Figure 11 would cause the lines to rotate counterclockwise about the 2.04-m intercept, and the calculated ice thickness curve would became horizontal, as it should be. Therefore, good EM31 conductivity measurements should provide for a determination of sea ice thickness either for when the instrument is resting on the ice surface or when it is elevated above the ice surface.

Seawater conductivity will be lower at a coastal site where a major river, such as the Mackenzie River in Canada, continues to flow into the ocean during the winter. No rivers flow into the Alaskan Beaufort Sea during the winter.

As previously stated, an EM31 instrument provides an apparent conductivity reading for a given instrument height above seawater. This reading is unique for a specific seawater conductivity and should allow deter-

Table 4. Theoretical versus measured EM31 conductivity as a function of instrument height above 2.04-m-thick sea ice and instrument tilt angle correction required to produce agreement between the theoretical conductivity for the vertical co-planar coils on the EM31 and the actual instrument field reading.

EM31 dist. to seawater (m)	*Theoretical conductivity* *Hor. coil (mS/m)*	*Ver. coil (mS/m)*	*EM31 reading (mS/m)*	*Angle correction (°)*	*New cond.* ver. coil (mS/m)*
2.04	292	239	240	0	—
2.31	257	197	211	3	210
2.59	223	162	172	3	174
2.89	192	133	150	5	149
3.16	165	110	126	6	126
3.45	144	93	112	8	112
3.73	125	79	98	9	98
4.02	108	67	85	10	85
4.30	94	57	72	10	72
4.59	82	49	64	11	64
4.87	72	42	54	11	55

* New theoretical vertical coil conductivity value = Ver. coil conductivity × cosθ + Hor. coil conductivity × sinθ .

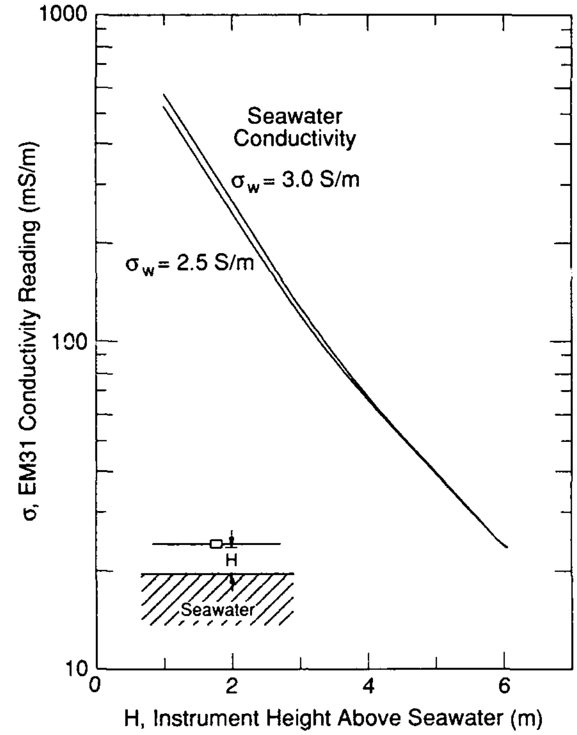


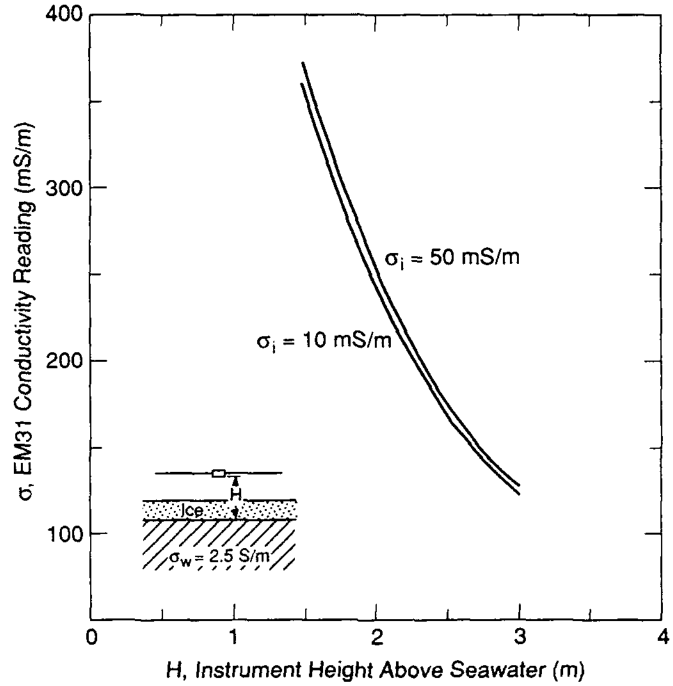
Figure 13. Theoretical EM31 conductivity reading versus instrument height above 2.5- and 3.0-S/m conductivity seawater.

mination of instrument–seawater stand-off distance. During the winter, the seawater under the Arctic Ocean pack ice has a conductivity of 2.5 ± 0.05 S/m. An analysis was made to show how an EM31's conductivity reading should vary with elevation above seawater of 2.5 S/m and an extreme seawater conductivity of 3.0 S/m. The results are shown in Figure 13 for vertical coplanar antenna coils. For heights above about 3 m, there is no appreciable difference in instrument reading versus seawater conductivity; there is, however, progressively greater difference as the instrument is brought closer to the water. For example, when the instrument is 1 m above seawater having a 2.5-S/m conductivity, the EM31 reading would be about 520 mS/m. However, this same reading over 3.0-S/m-conductivity water would occur when the instrument was about 1.1 m above the surface. This 10% error for the extreme seawater conductivities used indicates that the very low offshore Arctic Ocean conductivity variations will not significantly affect the ice thickness determinations.

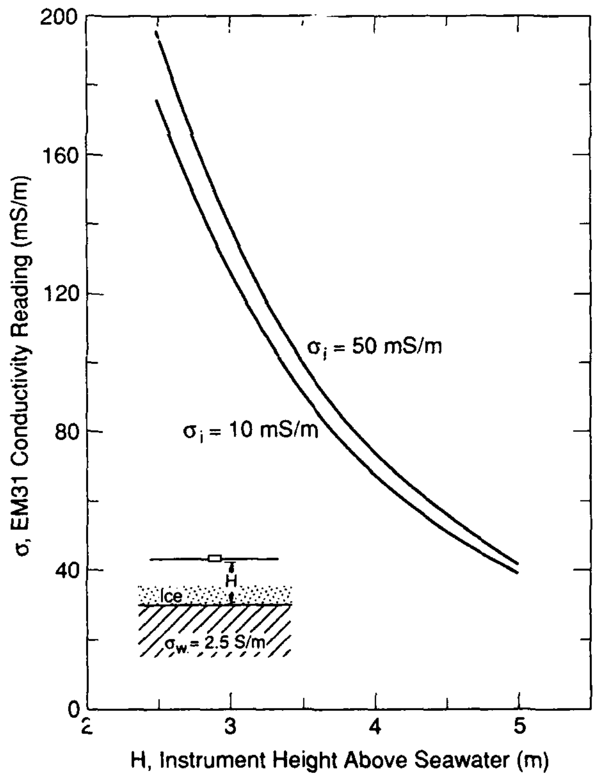
Another series of calculations was made to show how an EM31's conductivity reading should vary as the instrument is moved from the surface of 1.5- and 2.5-m-thick sea ice to some elevation above ice floating on seawater having a conductivity of 2.5 S/m. In this analysis, bulk sea ice conductivities of 10 and 50 mS/m were used. The latter is a high value that may represent warm, high-brine-volume sea ice. The former value is a reasonable value for arctic winter pack ice. The results are plotted in Figure 14. As may be inferred from these figures, the error, caused by the two bulk sea ice conductivities used, in the distance to the seawater, as determined from the instrument conductivity reading, is on the order of 5%. This indicates that the response from the seawater as measured by the instruments will not be significantly affected by sea ice conductivity variations.

An EM31 instrument is best used resting on the ice surface to avoid potential measurement error associated with tilting of the antenna coils. This would be particularly desirable on thick ice to maximize the received signal and to allow thick ice to be measured. If the instrument must be carried, then some provision should be made to show the operator whether or not the instrument is level.

If the instrument conductivity reading is to be used to infer ice thickness, then a simple table or graph affixed to the instrument cover could be used. Such a graph is



a. 1.5-m-thick ice.



b. 2.5-m-thick ice.

Figure 14. Theoretical EM31 conductivity reading versus instrument height above 2.5-S/m-conductivity seawater covered with ice of 10- and 50-mS/m bulk conductivity (σ_i).

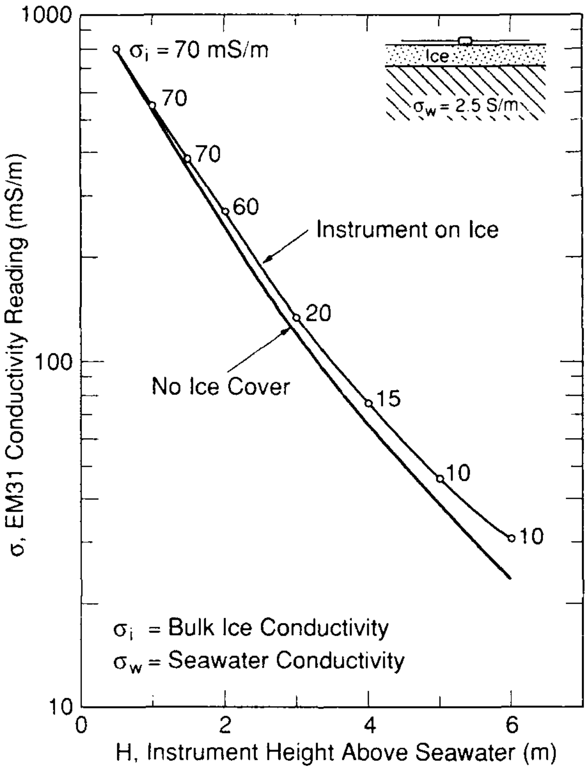


Figure 15. Theoretical EM31 conductivity reading versus instrument height above seawater. The ice is resting on water of 2.5-S/m conductivity and ice conductivity is shown to vary with thickness.

shown in Figure 15. This figure shows how the conductivity reading of an EM31 instrument should vary with sea ice thickness where the underlying seawater has a conductivity of 2.5 S/m. Another parameter used in construction of the graph is a variable bulk sea ice conductivity. These bulk conductivities versus ice thickness were obtained from recent work of Kovacs (1991). Note that the upper curve applies to an instrument resting on the surface, while the lower curve represents the instrument conductivity readings when no ice layer exists

The sea ice conductivities shown in Figure 15 represent reasonable upper limit values for the given ice thickness. Figure 15 is instructive because it indicates that the error associated with ignoring sea ice conductivity and assuming that an air layer exists between the instrument and the seawater will have a minimal effect on the estimated ice thickness. This is especially true for ice under 3 m thick.

GENERAL COMMENTS

Some of the data obtained with the Geonics EM31 and the Flow Research ice thickness processor module showed excessive variation from the drill-hole-measured ice thickness. However, measurements on first-year sea ice from about 0.7 to about 3.5 m thick, with a snow cover, indicated that the EM31-PM instrument was providing reasonably good estimates, even if they weren't accurate enough for our research. The unsatisfactory ice thickness measurements were generally obtained in areas of deformed ice where the measured electromagnetic response was adversely affected by conductive inhomogeneities associated with the submerged ice block structure.

Further testing of the EM31-PM instrument on a ladder produced ice thickness results that varied with instrument calibration procedure. This should not occur. However, other inconsistencies between instrument-determined sea ice thickness and direct tape-measured distances may have resulted from tilting of the antenna coils. Given this mixed review, another field test of the module's measurement performance is needed.

Use of the EM31-PM instrument in the field proved frustrating. The instrument frequently quit at temperatures below −15°C. We also encountered lithium battery problems. On several occasions one battery, out of the set of ten used to run the system, would drop in voltage. This drop would shut down the unit until the bad battery was found (back in "town") and replaced. This low battery problem caused measurement delays and may also have caused the cold weather shutdown problem mentioned above. When the instrument was picked up in Kent, Washington, new batteries for the instrument were also obtained. Therefore, the batteries should have been good if they were recently manufactured ones.

There is good reason to believe that a standard EM31 instrument can be used to determine sea ice thickness from about 0.7 to 5 m, to within an accuracy of ±10% of the tape-measured value. For this, the instrument's conductivity reading and a table or graph could be used; such a graph is presented in Figure 15. It may well be possible to achieve ice thickness determinations within 5% of the actual thickness when on ice of uniform thickness. However, further field tests would be needed to verify this.

In the absence of a theoretical analysis, the EM31 may be calibrated on the sea ice by simply recording the instrument conductivity reading made at a number of heights above the ice/water interface and constructing a graph similar to that presented in Figure 4. This calibration procedure needs only to be done once for arctic sea ice sounding, because the conductivity determined by the EM31 is based on the use of the measured quadrature phase response, the zero level of which "is designed to stay at the correct value over the life of the instrument over wide temperature excursions."* However, a calibration check would certainly be appropriate at a location where under-ice water conductivity may not be known.

In this report we addressed the use of EMI sounding to measure sea ice thickness in the Arctic Ocean. The presentation is specific to areas where the under-ice water depth is in excess of 6 m. In shallower waters, the response from the third layer, the seabed, needs to be addressed. This is beyond our scope here.

It should be kept in mind that EMI sounding does not give a point measurement, but provides an "average" ice thickness for an area having a diameter of about three times the height of the instrument above the seawater. Therefore, EMI sounding of multi-year sea ice thickness may result in significant errors where the bottom of the ice has rough, short-period undulations. This relief is not uncommon and must be taken under consideration when multi-year sea ice soundings are made using EMI.

* Personal communication with J.D. McNeill, Geonics, Ltd., 1990.

LITERATURE CITED

Anderson, W.L. (1979) Computer programs; numerical integration of related Hankel transforms of order 0 and 1 by adaptive digital filtering. *Geophysics*, **44** (7): 1287–1305.

Echert, D.C. (1986) Electromagnetic induction remote sensing of sea ice thickness. Kent, Washington: Flow Research Co., Inc., Flow Technical Report No. 388.

Echert, D.C., G.B. White and A. Becker (1989) Electromagnetic induction sensing of sea ice thickness and conductivity. Kent, Washington: Flow Research Co., Inc., Flow Technical Report No. 492.

Geonics, Ltd. (1984) Operating manual for EM31-D non-contacting terrain conductivity meter. Mississauga, Ontario, Canada.

Hoekstra, P., A. Sartorelli and S.B. Shinde (1979) Low frequency methods for measuring sea ice thickness. *International Workshop on the Remote Estimation of Sea Ice Thickness, Memorial University, St. John's, Newfoundland, Canada*, pp. 313–330.

Hoekstra, P. (1980) Theoretical and experimental results of measurements with horizontal magnetic dipoles over sea water to measure ice thickness and water salinity. Geo-Physi-Con Co., Ltd., Calgary, Alberta (confidential document).

Kovacs, A. (1991) Preliminary results of the 1990 Alaska remote sounding of sea ice thickness study. USA Cold Regions Research and Engineering Laboratory, Internal Report (unpublished).

Kovacs, A. and S.J. Holladay (1989) Development of an airborne sea ice thickness measurement system and field test results. USA Cold Regions Research and Engineering Laboratory, CRREL Report 89-19.

Kovacs, A., R.M. Morey and G.F.N. Cox (1987a) Modeling the electromagnetic property trends in sea ice, Part I. *Cold Regions Science and Technology*, **14**(3): 207–235.

Kovacs, A., N.D. Valleau and S.J. Holladay (1987b) Airborne electromagnetic sounding of sea ice thickness and sub-ice bathymetry. *Cold Regions Science and Technology*, **14**(3): 289–311.

Liu, G. and A. Becker (1990) Two-dimensional mapping of sea-ice keels with airborne electromagnetics. *Geophysics*, **55**(2): 239–248.

Sinha, A.K. (1976) A field study for sea ice thickness determination by electromagnetic means. Geological Survey of Canada, GSC Paper 76-1C, pp. 225–228.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
June 1991

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Evaluation of a Portable Electromagnetic Induction Instrument for Measuring Sea Ice Thickness

5. FUNDING NUMBERS
C: N6845286MP6003
C: N000140WX4B714

6. AUTHORS
Austin Kovacs and Rexford M. Morey

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, N.H. 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER
CRREL Report 91-12

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Oceanographic and Atmospheric Research Laboratory
and Naval Civil Engineering Laboratory
U.S. Department of Navy

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

Available from NTIS, Springfield, Virginia 22161.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Field trials using a man-portable Geonics, Ltd., EM31 electromagnetic induction sounding instrument, with a plug-in data processing module, for the remote measurement of sea ice thickness, are discussed. The processing module was made by Flow Research, Inc., to directly measure sea ice thickness and show the result in a numerical display. The EM31–processing module system was capable of estimating ice thickness within 10% of the true value for ice from about 0.7 to 3.5 m thick, the oldest undeformed ice in the study area. However, since seawater under the Arctic pack ice has a relatively uniform conductivity (2.5 ± 0.05 S/m), a simplified method, which can be used for estimating sea ice thickness using just an EM31 instrument, is discussed. It uses only the EM31's conductivity measurement, is easy to put into use and does not rely on theoretically derived look-up tables or phasor diagrams, which may not be accurate for the conditions of the area.

14. SUBJECT TERMS
Electromagnetic ice sounding — Sea ice
Remote sea ice measurement — Sea ice thickness

15. NUMBER OF PAGES
23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL